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X-ray emission from early-type galaxies

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Abstract.
The last ~10 years have seen a large progress in the X-ray investigation of early-type galaxies of the local universe, and first attempts have been made to reach redshifts $z > 0$ for these objects, thanks to the high angular resolution and sensitivity of the satellites *Chandra* and *XMM*−Newton. Major advances have been obtained in our knowledge of the three separate contributors to the X-ray emission, that are the stellar sources, the hot gas and the galactic nucleus. Here a brief outline of the main results is presented, pointing out the questions that remain open, and finally discussing the prospects to solve them with a wide area X-ray survey mission such as *WFXT*.

Key words. Galaxies: elliptical and lenticular, cD – Galaxies: evolution – Galaxies: ISM – Galaxies: nuclei – X-rays: binaries – X-rays: galaxies

1. Introduction

X-ray investigations of early-type galaxies[1] (hereafter ETGs) of the local universe began in the 1980s with the *Einstein* satellite, and revealed that the total X-ray luminosity originates from a combination of hot interstellar gas and low-mass X-ray binaries (LMXBs; Fabbiano 1989). With the advent of the *ROSAT*, *ASCA* and then *Chandra* and XMM-Newton eras, our knowledge of all the components of the X-ray emission has deepened considerably: among stellar sources by far the largest contribution comes from LMXBs, and it has been quantified; a hot gaseous halo (with a temperature of ~few million degrees) can be present with largely varying amounts; another important galactic component, a supermassive black hole (MBH) believed to be common at the center of ETGs and a relic of the past quasar activity, showed luminosities ranging continuously from the lowest detectable levels (e.g., that of a bright LMXB in Virgo) to values typical of Seyferts. The combined study of the hot gas and low luminosity nuclei turned out to be a crucial tool to build our understanding of MBH accretion and feedback in the local universe.

The results above are based on few tens of ETGs accurately studied with *Chandra* and *XMM*-Newton, whose archives contain at present roughly two hundreds ETGs with a specific pointing, located within a distance of ~ 100 Mpc. In this work I review briefly the main advances concerning the three major emission components (the stellar emission in Sect. 2, the hot gas in Sect. 3 and the galactic nuclei in Sect. 4), indicating also the needs for further

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[1] This work is devoted to ”normal” early-type galaxies, where the X-ray emission is not dominated by an AGN, and keeps below $\sim 10^{42}$ erg s^{-1}.

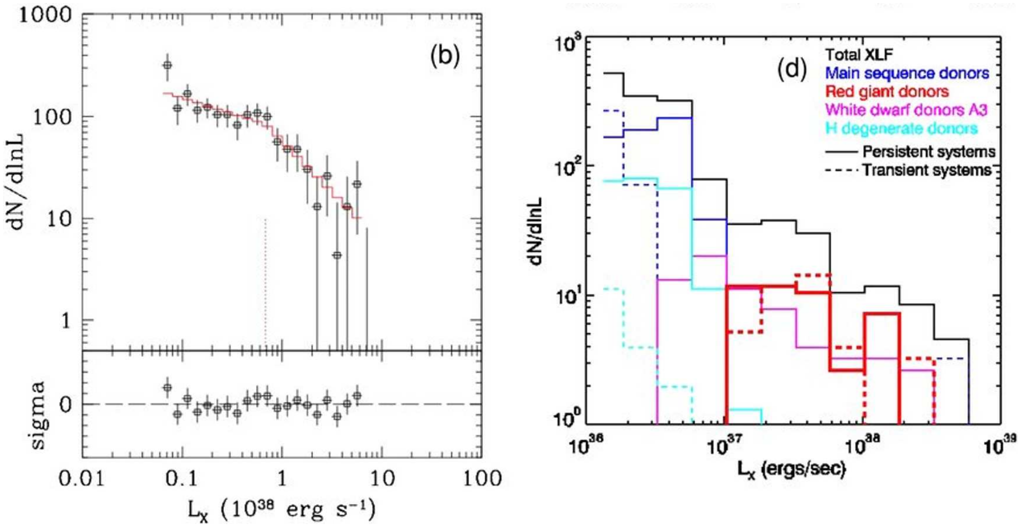

Fig. 1. The 0.3–8 keV luminosity function of LMXBs for three hot gas poor ETGs with deep *Chandra* pointings (Sect. 2) on the left, and the theoretical prediction of Fragos et al. (2008) on the right (from Kim et al. 2009).

investigation; in Sect. 5 I summarize the current scant and sparse knowledge of the X-ray properties of ETGs beyond the local universe; in Sect. 6 I discuss the prospects to address a few important science goals with *WFXT*.

2. Stellar sources

The stellar X-ray emission of ETGs is contributed by a population of weak sources ($L_X < 10^{34}$ erg s^{-1}) as late type stellar coronae, cataclismic variables, and coronally active binaries (Pellegrini & Fabbiano 1994), and by the more luminous LMXBs, associated with an old stellar population and powered by accretion from a low-mass late-type star onto a compact stellar remnant, a neutron star or a black hole. The origin and evolution of the collective LMXB population of ETGs is the subject of much discussion (Fabbiano 2006); LMXBs are found in both the stellar field and globular clusters, but their incidence per unit stellar mass is much higher in the latter, suggesting the importance of a dynamical formation mechanism.

Exploiting the sub-arcsecond angular resolution provided by *Chandra* the nature of the stellar contribution to the X-ray emission could be better constrained, especially with deep pointings at ETGs (almost) devoid of an important contaminant such as the hot gas (Brassington et al. 2008, 2009). In this way the collective contribution of the weak population could be estimated in NGC3379 (Revnivtsev et al. 2008). Luminous ($L_X > 10^{36}$ erg s^{-1}) pointlike sources could instead be individually detected and their X-ray luminosity function (XLF) be built in a number of galaxies, the deepest studies being those for NGC3379, NGC4278 and NGC4697 (Kim et al. 2009, see Fig. 1), and NGC5128 (Voss et al. 2009). One major goal is to calibrate the dependence of the collective X-ray emission from LMXBs on the galaxy stellar mass or luminosity, age and globular cluster specific frequency. The high luminosity end of the XLF ($L_X >$several$\times10^{37}$ erg s^{-1}) and the collective luminosity of the whole LMXB population as a function of the galactic luminosity are now reasonably known, with a possible dependence also on the globular cluster specific frequency still to be evaluated (Kim & Fabbiano 2004; Gilfanov 2004; Kim et al. 2009). The features in the observed XLFs that are being discovered (as breaks at high and low luminosities, possible bumps, differences for field and globular cluster sources) represent important inputs to theoretical models for LMXB formation and evolution, as those built with the advanced population synthesis code StarTrack (Fragos et al. 2008, 2009). These models also predict the evolution of the XLF with galaxy age, and then the collective (hard) emission from LMXBs; such predictions are useful for investigations of ETGs at higher redshift that are attempted currently (Sect. 5) and will flourish with *WFXT* (Sect. 6).

3. Hot interstellar medium

Chandra observations allowed to separate the contribution of stellar sources and hot gas, as well as emission coming from different spatial regions within galaxies, obtaining the best definition ever for the hot gas properties (e.g., Kim & Fabbiano 2003; Humphrey & Buote 2006). It is now proven that in optically luminous ETGs the soft interstellar gas can be present with largely varying amounts (Fabbiano 1989; Pellegrini & Ciotti 1998; Sarazin et al. 2001), producing a scatter in L_X up to a factor of 100 at fixed galactic optical luminosity (Fig. 2); in optically faint ETGs instead the X-ray emission is always dominated by LMXBs (David et al. 2006; Pellegrini et al. 2007; Trinchieri et al. 2008).

The hot ISM provides fuel for the central MBH and absorbs energy from nuclear outbursts, in a complex cycle whose mechanism is not yet fully understood (e.g., Forman et al. 2005; Baldi et al. 2009; Ciotti et al. 2010). A compilation of radial temperature profiles for the hot gas shows that the radio luminosity decreases continuously as gradients in the profiles change from positive to negative, as if the profiles were reversing the temperature gradient over time following an activity cycle (Diehl & Statler 2008). Also the environment in which ETGs reside can influence the hot gas coronae, having an effective impact on their outer temperature gradient (Diehl & Statler 2008), and on their size and luminosity via stripping, sloshing, compression, conduction (Sun et al. 2007); the environment is also important for the injection of metals

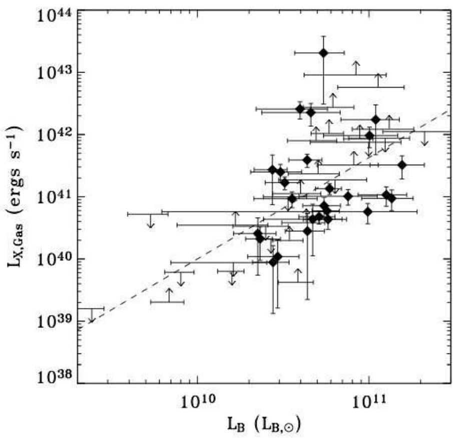

Fig. 2. The 0.3–5 keV luminosity of the hot gas as a function of absolute blue galactic luminosity, for a sample of ETGs of the local universe in the *Chandra* archive (from Diehl & Statler 2007).

from ETGs in the intracluster medium (e.g., Kim et al. 2008a). The sample of ETGs for which all these phenomena have been investigated is however limited, and real samples in a statistical sense (i.e., made of thousands of objects) are needed to establish clearly the effects of a surrounding medium, of the interactions with neighbours, of feedback, possibly dividing galaxies based on mass, age, and kinds of environment.

4. Low luminosity MBHs

Thanks to *Chandra*'s angular resolution, for the first time measurement of the nuclear X-ray emission down to values as low as 10^{39} erg s^{-1} and out to distances of ~ 60 Mpc were obtained. MBHs of the local universe turned out to be typically very sub-Eddington emitters (Pellegrini 2005; Gallo et al. 2008) and their radiative quiescence was interpreted in terms of radiatively inefficient accretion (RIAF; Narayan & Yi 1994), possibly with the mechanical power dominating the total energy output of accretion (e.g., Allen et al. 2006). From the sample available, there appears to be only a weak relation of the nuclear luminosity with the MBH mass or with the galactic hot gas content, with a very large disper-

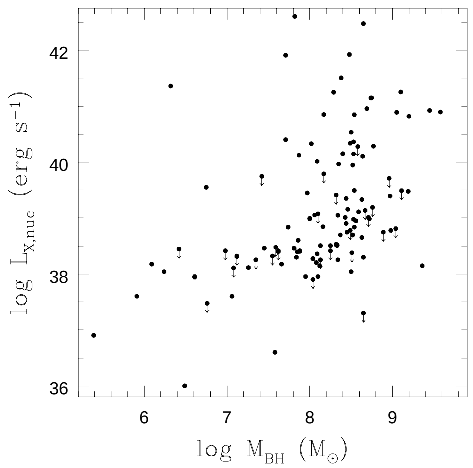

Fig. 3. The 2–10 keV nuclear luminosity as a function of the MBH mass for a sample of ETGs of the local universe in the *Chandra* archive (Pellegrini 2010).

sion dominating the two relations (Pellegrini 2010; Fig. 3). The modeling of the observables (mainly the nuclear spectral energy distribution from radio to X-rays, and the mass accretion rate derived from the gas density and temperature close to the accretion radius) allows to establish the origin of the nuclear X-rays (standard disk plus hot corona, RIAF, jet, or a combination of them; e.g., Fabbiano et al. 2003; Ptak et al. 2004), and derive important clues on the modality of the MBH feeding, or the kinetic feedback from jets, and then on the co-existence of MBHs and host galaxies. Despite many efforts applied to observational data, accretion in the local universe remains poorly known, while its knowledge is important for a complete understanding of the MBH-host galaxy coevolution process. Current believes are that MBHs spend most of their life in the RIAF regime (Hopkins et al. 2006; Ciotti et al. 2010), an accretion state expected to be efficient in producing outflows and jets, and then to correspond to the "radio-mode" of MBH feedback invoked in semi-analytic studies and hydrodynamic simulations of galaxy formation (e.g., Croton et al. 2006).

5. Beyond the local universe

Many surveys with different depths and fields of view have been performed so far with *Chandra* and *XMM*–Newton; for each of them typically a sample of only $<\sim 100$ ETGs could be built, so that only few results could be obtained about the evolution with redshift of ETGs. The deepest study was conducted in the GOODS fields, where 40 ETGs divided in two redshift bins, of $z < 0.5$ and $0.5 < z < 1.2$, showed luminosity evolution, by which ETGs were brighter in the past; this could be due to passive evolution of LMXBs (Ptak et al. 2007, Sect. 2). In the ECDF-S regions, 539 optically selected ETGs with $0.1 < z < 0.7$ and $R < 24$ corresponded to the detection of 13 luminous ETGs plus 32 AGNs, and the characterization via the stacking procedure of the others (Lehmer et al. 2007). When divided in four z-bins from $z = 0.25$ to $z = 0.66$, and two luminosity bins separated at $L_B \sim 10^{10} L_{B\odot}$, the optically faint samples seem to show an increase in L_X with z, while the brighter ones keep within the range of values observed locally, as due to a long-lasting ($\sim$ 6 Gyr) balance between heating and cooling of the hot gas coronae. The wide area ($\sim$ 30 deg^2) ChaMP survey based on archival *Chandra* fields (Kim et al. 2008b) for a sample of $<\sim 100$ ETGs at $0.01 < z < 0.3$ finds the minimum X-ray–to–optical ratio (likely the baseline contributed by LMXBs) to be constant with redshift. In the wide area (9.3 deg^2) XBoötes survey studied with a mosaic of 5 ks pointings, the hardness ratio of 2968 stacked ETGs evolves from $z = 0.2$ to $z = 0.4$, i.e., the average spectrum becomes harder with increasing z, which could be due to an increasing AGN contribution (Watson et al. 2009). A collection of data from the *Chandra* Deep Fields to XBoötes, the shallowest survey, produced a sample of 101 ETGs up to $z \sim 1.4$, that show no significant luminosity evolution when divided in two z-bins centered at 0.17 and 0.67 (Tzanavaris & Georgantopoulos 2008). Overall these investigations are heterogeneous, based on different selection criteria, and plagued by the limited numbers of ETGs in the samples, so that the results can be considered only preliminary.

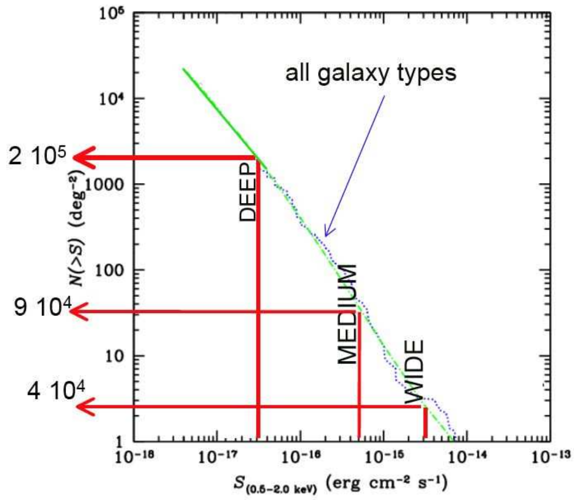

Fig. 4. The number of galaxies to be detected in the three *WFXT* surveys (indicated by the arrows), based on a recent estimate extrapolated to low fluxes (green line) of the number $N(> S)$ of galaxies with 0.5–2 keV flux S larger than the value on the x-axis (Tzanavaris & Georgantopoulos 2008). The green line referes to both late and early types, with the galaxies in the sample roughly equally divided between the two types.

6. WFXT

As discussed in the previous Sections, X-ray information about ETGs in the local universe (distance < 100 Mpc) is mostly based on a number of $<\sim 200$ galaxies that benefitted of pointed observations with *Chandra* and *XMM*-Newton. Beyond the local universe, only samples with < 100 objects could be built, with very limited information on them; future extensions of the surveys performed so far are not likely to produce substantial improvements. Statistical studies, as the building of the ETG's LF and the search for its possible evolution, or the study of the dependence of the X-ray emission on different kinds of environment, require far larger samples. *WFXT* is designed to produce a dramatic advance over existing or planned missions in combined solid angle and sensitivity, keeping a good angular resolution of 5″ (see, e.g., Rosati in these proceedings); the energy band (0.4–7 keV) is sensitive to both the soft hot gaseous emission and the hard stellar/AGN contribution. With the three surveys (wide of 20000 deg^2, medium of 3000 deg^2 and deep of 100 deg^2) *WFXT* could drastically increase the number of detected ETGs and revolutionize the field (see Fig. 4, based on the flux limits indicated by Rosati). For example, the deep survey is expected to produce $\sim 10^3$ times the solid angle of the *Chandra* Deep Fields at the same sensitivity. An ETG with a (conservative) size of ~ 20 kpc will have an angular dimension of 10″ at $z = 0.1$ and 5″ at $z = 0.3$, beyond which it will appear as a pointlike source for *WFXT*. Using flux limits for point sources, an average ETG X-ray luminosity of 10^{41} erg s^{-1} will be detected out to $z = 1$, 0.3 and 0.1 respectively in the deep, medium and wide surveys. The combination of the X-ray data with photometric and spectroscopic information at other wavelengths like those provided by current and planned surveys (as 2MASS, SDSS, Galex, LSST, SDSSIII/BOSS, ...) should give distances and the main galactic parameters.

The wide survey then could detect ~few10^4 ETGs mostly within $z = 0.1$, and allow to build the first really large sample of ETGs in the local universe. More than $\sim 10^3$ objects could be studied with enough detail to measure gas properties, and distinguish stellar and nuclear luminosities; angular resolution could enable to detect sharp features in the hot gas as shocks, holes, rims. This could make up a baseline for medium/high z studies. Sample questions to be tackled with a large database include: how is feedback working at all galactic luminosities? with what duty cycle? is the large dispersion in hot gas content (Fig. 2) related to nuclear activity, galaxy structure, or environment?

At $z > 0.1$ (a lookback time larger than 1.3 Gyr for standard cosmological parameters), instead, the three main components (LMXBs, hot gas and nuclei) should be revealed mostly from their integrated contribution to the X-ray spectra, and their evolution could be studied. For example, the LMXB's contribution, determined at $z = 0$ as described in Sect. 2, at $z > 0$ should be higher than in local ETGs, depending on epoch of major star formation (Sect. 2). The evolution of hot gas and nuclear activity (respectively contributing to the soft and hard bands) should give important insights on the feedback process, revealing for example whether the hot gas content and temperature evolve with time, and the nuclear luminosity increases. In the deep survey there will be detections of ETGs out to $z \sim 1$, to study the transition of accretion in the radio mode and its evolution in this state (Sect. 4).

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